Lenses for the Photolithographic System

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The edge definition, maximum complexity and accuracy of details in photolithographic masks are limited by the performance of the lenses in the system. The tolerances on exposure, sensitivity and uniformity of the photosensitive materials, and processing are dependent upon the images formed exceeding the minimum quality required. The lenses in this system have been designed and fabricated to achieve the best practical performance at this time in order to obtain the largest tolerances possible. This paper details the design parameters chosen, the constructions used and the performance obtained by each of the lenses in the system.

I. INTRODUCTION

There are two classes of photographic mask-making systems. In the first class, the pattern is generated through a lens as in a cathode-ray-tube plotter or primary pattern generator (PPG), or a lens is used to reduce the size of the pattern to that of the circuit being made. The maximum complexity of pattern in this type of system is limited by the resolution that can be obtained over the field of a lens.

A second class of systems uses a lens imaging a single small spot of light that is moved over an area and modulated to write a pattern. In this type of pattern generator the complexity of pattern is limited only by the minimum spot size and the area covered. This system must be used to draw the mask at the same scale as the final circuit or the lens in a reduction camera would limit the resolution.

Systems in the first class have been chosen for the mask laboratory in spite of the resolution limitations because of the speed and flexibility of the lens type systems for making a wide variety of masks. As a result the lenses in the system are the principal limitation on the maximum complexity of patterns that can be produced and on the quality of the images.

The performance of lenses is limited by the wavelength of light, the aperture of the lenses, and the aberration correction of the lenses. The wavelength of visible light is about half a micron, and it is theoretically possible to obtain light distributions in an image having cycles of light and dark of about one-half-micron width. Blue light can be imaged with better resolution because it has a shorter wavelength than green or red light. The wavelength that can be used in making masks is limited by the sensitivity of the photographic materials, the available light sources and the transmittance of the glasses used in the lenses and as a substrate for the photosensitive materials.

The resolution is also limited by diffraction. It would be necessary to bring light to the image from a cone subtending an angle of 180° to resolve spatial images with periods of one wavelength. A smaller angle of light to an image will limit the resolution to larger detail. The large apertures of the lenses used in this system are required for resolution of the detail in the masks rather than to collect light.

The resolution of a lens may also be limited by aberrations. A single lens element with spherical surfaces will not image the light passing through it from a point in the object to a point in the image. Aspheric surfaces could be used to do this for a point on the axis of the system but not for points off axis. These defects in the imagery can be greatly reduced by combining many elements designed to compensate for the aberrations. It is not possible to reduce these aberrations to zero but they can be made smaller than the diffraction effects by using complex combinations of lenses.

II. MODULATION TRANSFER FUNCTIONS

A convenient measure of the quality of an optical image is the modulation transfer function (MTF). This is a curve of the contrast that is obtained in the image of a sinusoidal intensity target as a function of the spatial frequency of the target. Figure 1 shows a series of MTF curves for perfect lenses of various aperture ratios. The MTF varies from 0 to 1.0 and is the ratio of the contrast in the image to that of the target. The spatial frequency scale is in cycles per mm and covers the general range of interest in mask-making systems. As you can see in Fig. 1, the smaller the f/number, the better the contrast and the higher in spatial frequency it extends. Thus, to get a high quality image of 25μ lines in a reduction camera may require only an $f/8$ cone angle to the image, but good 1μ lines in a step-and-repeat camera require a lens of $f/2$ or faster.

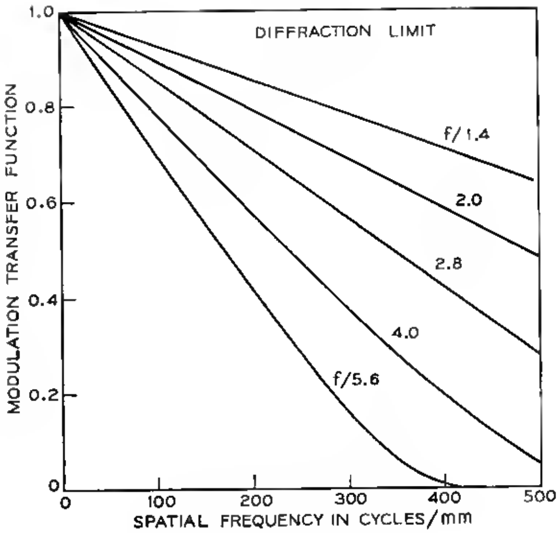

Fig. 1—MTF as a function of spatial frequency in an image formed by a cone of light of the indicated "f" number.

This requirement for low "f" numbers for high resolution may seem strange to those who are used to stopping down the lens to get a sharper image. This is because conventional camera lenses are limited in performance by their aberrations and stopping down the lens reduces these aberrations. The best resolution is probably obtained at about $f/8$; the image gets poorer when stopped down beyond that because of the diffraction limits shown in the MTF curves. Photographic lenses are often used in low-light conditions and the value of the increased speed obtained by increasing the aperture is more important than the loss in resolution caused by the aberrations.

In contrast, the large apertures of lenses for mask-making systems are almost always picked for resolution rather than speed. It is therefore necessary to reduce the aberrations to values that are small in comparison to their diffraction effects. There is still a compromise region. A lens for a 2.5μ linewidth mask should have an MTF of over 60 percent at 200 cycles/mm. This could either be obtained with a perfect $f/4$ lens or an $f/3$ lens with some aberrations. It could also be obtained with an $f/2$ lens with larger aberrations but unless the exposure speed of the lens were critical, the greater complexity of the

$f/2$ lens would make it more expensive and prone to larger errors in fabrication.

A second reason to select the smaller aperture is its increased depth of focus. When projecting an image directly onto a non-flat silicon wafer, this can be of major importance. In making masks on glass it determines the flatness tolerance; in all cases it determines the accuracy to which the cameras must be focussed and the stability of this focus.

III. SYSTEM CONSIDERATIONS

The lenses used in this mask-making system have been designed for practical operation in a production system. The parameters have been selected to advance the state of the art in each area and to obtain the largest tolerance possible in each operation of the mask system.

The performance of each part of the system is limited by the lens. The 26,000 address width of the pattern generator field is near the maximum that can be obtained with the aperture limits of the scanning system. The 5000 linewidth square field of the step-and-repeat camera is even more challenging to the lens designer for the small image involved. The reduction-camera lenses are not as difficult but have been designed for higher performance and therefore greater tolerances in use.

All of the lenses have been designed without major consideration of cost as even small improvements in performance would result in operating savings in excess of any reasonable cost.

IV. LENS DESIGN

The design of specialized lenses of this type is far ahead of the ability to manufacture them with uniform quality. In recent years automatic lens design programs have been developed which efficiently find the optimum design from each starting point while placing the desired importance on each characteristic. For instance, it has been found that designs of the types used are capable of essentially zero field distortion. It would be difficult using manual design techniques to find designs completely free of distortion. With automatic design programs, a small weight on distortion will cause new designs to be selected by the programs that are free of distortion until it is necessary to compromise other characteristics. The designer can then see just what must be sacrificed in one characteristic for gain in the other.

It is either necessary for the lens designer to learn all of the other parameters of the mask system or for the system designer to under-

stand the lens design difficulties to arrive at suitable system compromises. The development of automatic design programs has made it reasonable for the system designer to explore the design of the lens while designing the system. A variety of lens designs for the lenses of this program were explored by the systems designer although the final lenses were designed and constructed by an experienced lens design group at Tropel, Inc.* In this manner, the system parameters were selected, a suitable performance target could be determined, and a tentative choice between performance and complexity could be made prior to final lens design.

V. LENS ASSEMBLY

All of the lenses in the system have maximum wavefront aberrations of approximately $\lambda/4$. They have up to 14 air glass surfaces as well as two or more cemented surfaces. The quality of each of these surfaces must be very good so that the accumulations of the errors on the individual surfaces including the inhomogeneity of the glass does not approach the aberration tolerance. The centering and spacing of the elements must be of extraordinary quality to maintain the diffraction limited performance. Conventional techniques for measuring and controlling the centering and spacing of lens elements are not sensitive or accurate enough for lenses of this type. The lenses have been assembled by Tropel using new techniques that they have developed in recent years. We have carried out a program at the Laboratories to explore improved interferometric techniques that will make even better lens systems feasible.

VI. LENS EVALUATION

Lenses are now evaluated by photoelectrically measuring the modulation transfer function in a lens bench. This is done by scanning the image of a periodic target with a slit or the image of one slit with a second one and calculating the transfer function. For lenses of this quality, the slits must be extremely narrow and the measurement is limited by the photon noise of signals through the slits and the stability of the lens bench and air during the time of measurement. One measured curve is shown for the 3.5X lens but the measurement is not convincing as the curve goes above theoretical values at high frequency. Wavefront measuring methods are now being developed from which better MTF curves should be obtained.

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* Located in Fairport, New York.

VII. PATTERN GENERATOR LENS

The pattern generator lens has very special requirements. It must both collimate the laser beam before it is reflected from the polygonal mirror and then image the reflected beam to a flat focal plane on the photographic plate. The effective aperture position for the lens is at the surface of the mirror. The gaussian light distribution in the aperture of the lens is controlled by the illuminating laser beam. Although the lens is corrected at $f/10$, the writing beam fills the aperture with an $f/22$ cone angle which gives a 10μ-diameter gaussian distribution in the image. The code beam fills a larger aperture in the scan direction so that a higher modulation is obtained when the image scans the 7-μm bars and spaces of the code beam. The lens must provide a large amount of barrel distortion so that a constant angular rate of the scanning mirror provides a uniform linear scan in the focal plane. The combination of no vignetting of the laser beam in the lens and a uniform linear velocity of the scan gives a uniform exposure over the plate. Figure 2 shows the scanning lens and Fig. 3 shows the calculated MTF of this design.

VIII. REDUCTION-CAMERA LENSES

The reduction-camera lenses image the pattern generator plate onto HRP photographic plates. The mercury 435.8-nm spectral line is used so that only the monochromatic aberrations are critical. The lenses are correct for first-order axial and lateral color at this wavelength. The field angle is a compromise between camera length and aberration correction. The entrance pupil distance is the same for both the 3.5X

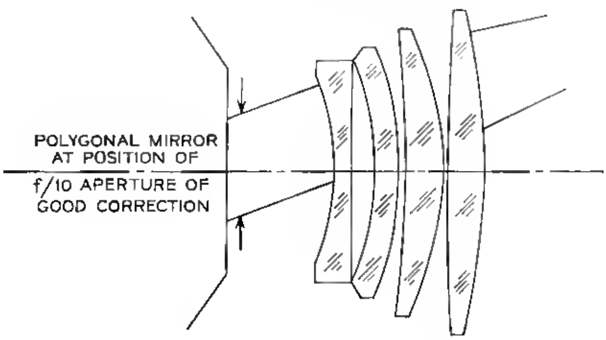

Fig. 2—Cross section of pattern generator lens.

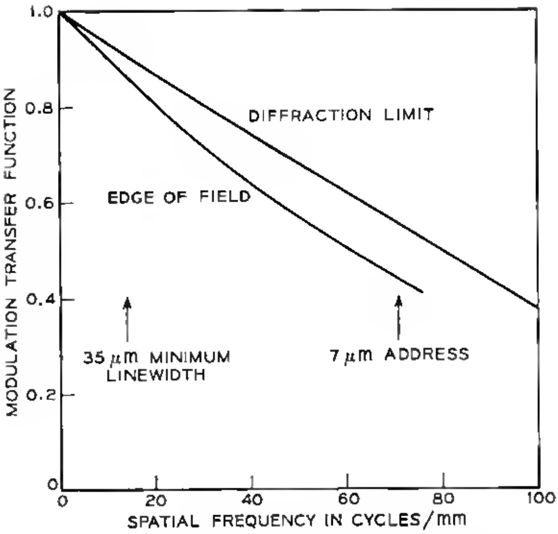

Fig. 3—MTF curves for the pattern generator lens on axis and at the edge of the field in relation to the fundamental frequency of the 7-μm address and 35-μm linewidth.

and 1.4X lenses so that the same illumination system can be used for both. Microflat glass plates are used in this camera so depth of focus is not important. The apertures have been selected to give best image quality and an iris is built into each lens so that they can be stopped down if poorer quality glass is used.

The 435.8-nm wavelength was selected as a compromise between the better resolution at the shorter wavelength than the more commonly used 546.0-nm line, and tbe smaller amount of scattered light in the green. The scattering in the blue is greatly reduced by using tbe dyed emulsion plates that are described in another article in this issue.

IX. 3.5X REDUCTION CAMERA LENS

The 3.5X reduction-camera lens shown in Fig. 4 is a seven-element double-Gauss type operating at $f/3.5$ and having a focal length of 17.7 cm. Efforts were made to use an eight-element design for better performance but the improvement was not judged sufficient to exceed the probable losses in an extra element. Figure 5 shows the MTF curves for this lens on axis and at the edge of the field along with the diffraction limit for the lens aperture used. The fundamental frequency

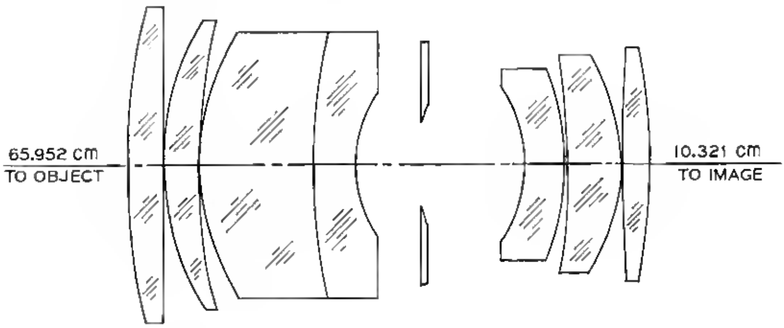

Fig. 4—Cross section of 3.5X reduction camera lens.

for a 10μ minimum linewidth used would be at 50 cycles per mm where the response is 70 percent or greater. There is significant response at a number of harmonics of this frequency to better reproduce sharp edges.

The intensity distribution for a square-wave object can be calculated from the response at the various harmonics in the source. Figure 6 shows the intensity distribution calculated for this lens from a 10μ-periodic square wave object, an isolated 10μ line at the center of

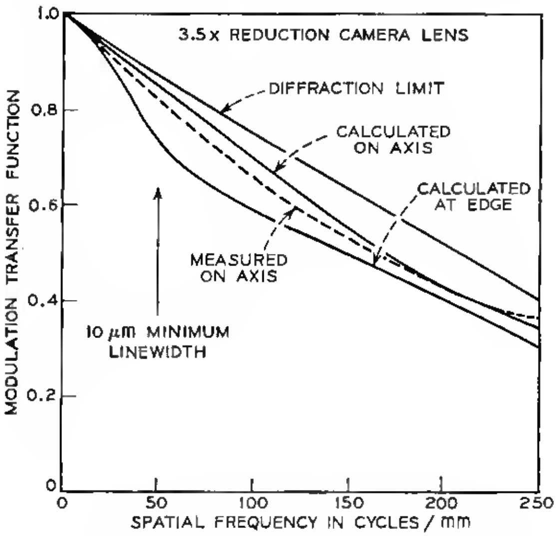

Fig. 5—Measured and calculated MTF curves for 3.5X lens.

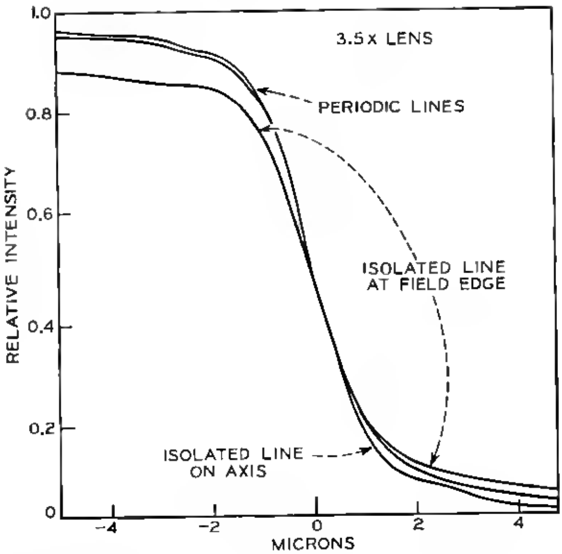

Fig. 6—Intensity distributions for 10-μm-wide periodic and isolated lines on axis and at the corner of the field of the 3.5X lens.

the field, and at the edge of the field. It is important that the slope of these curves at the edge of the line be large so that variation of exposure caused by light-source fluctuation, photographic-material sensitivity variation, and developing chemistry, time or temperature will not have a large effect on the linewidth developed from the image. As can be seen here, the isolated line and periodic lines would require a

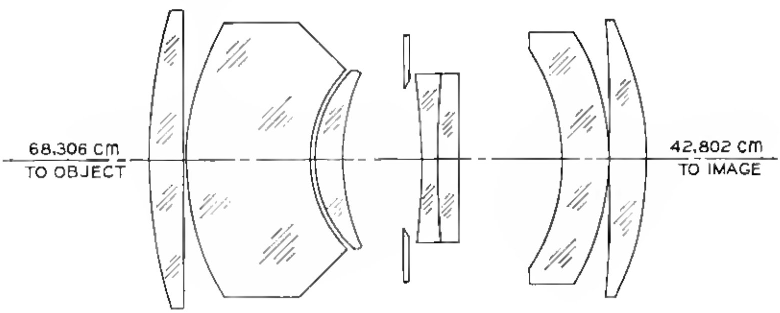

Fig. 7—Cross section of 1.4X reduction-camera lens.

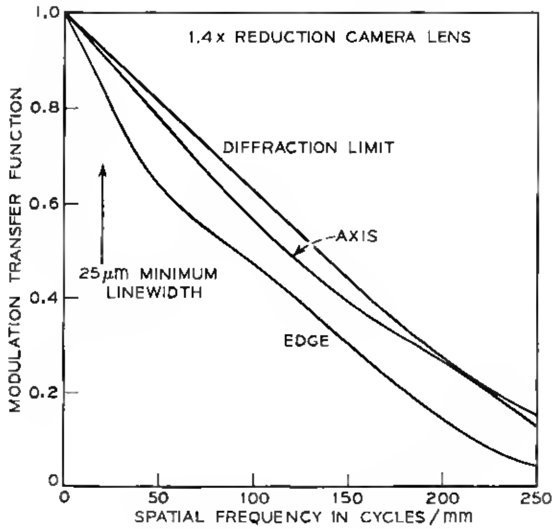

Fig. 8—MTF curves for the 1.4X reduction-camera lens.

slightly different exposure to both have correct linewidth. While this different exposure can be used to obtain accurate linewidth on masks having predominantly isolated or periodic lines, only a lens with a good MTF will give consistently accurate dimensions on all types of features.

X. 1.4X REDUCTION-CAMERA LENS

The outline of the 1.4X lens is shown in Fig. 7. While a double-Gauss type could have been used for this lens, this rather unusual configuration gave better performance for the specific requirement and the size is much smaller than the double-Gauss type.

The focal length is 32.4 cm and the overall length is 128.4 cm. The $f/4.15$ aperture provides a smaller cone to the image than the 3.5X lens but accepts a larger cone of light from the object providing better resolution compared to the finest line.

Figure 8 shows the MTF curves for the 1.4X reduction-camera lens and Fig. 9 shows the corresponding intensity distribution for periodic and isolated 25-μm lines. The 80 percent MTF at the fundamental frequency of the line results in a sharper line edge in the intensity profile and a resulting larger tolerance in exposure.

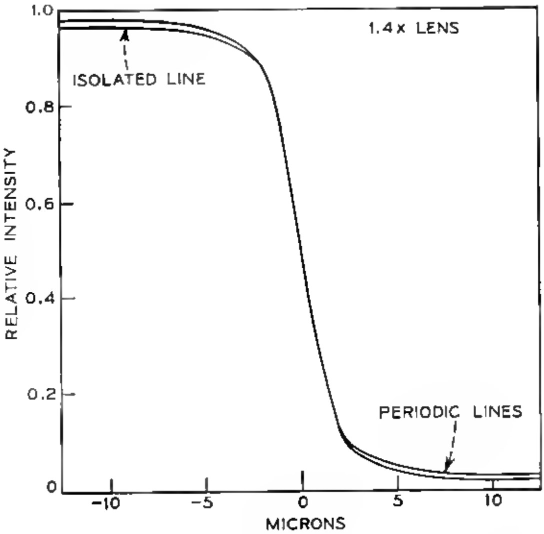

Fig. 9—Intensity distributions for isolated and periodic lines imaged by the 1.4X lens.

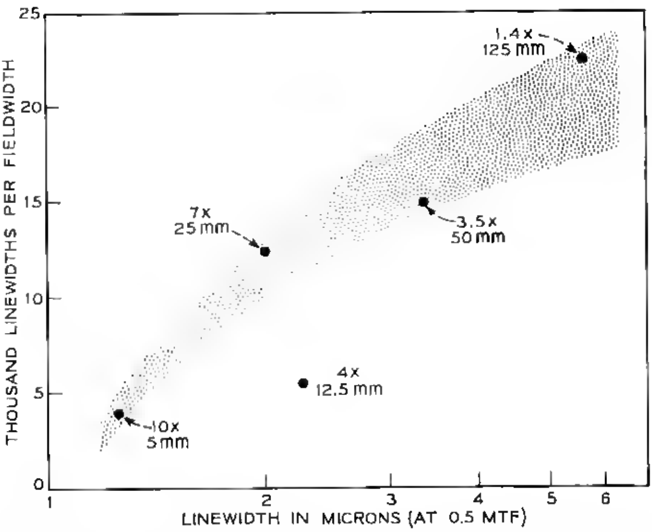

Fig. 10—Performance of a group of photolithographic lenses plotted as the number of linewidths per field width as a function of the linewidth at which 0.5 MTF is obtained.

XI. CAPABILITY OF GENERAL PHOTOLITHOGRAPHIC LENSES

The designs of the lenses in this system, including a 7X reduction-camera lens that has not been used, show the general range of performance that can be obtained. Figure 10 shows the number of thousands of linewidths per field as a function of the linewidth at 0.5 MTF. The shaded region indicates the area of reasonable design. There is not a smooth curve through these points as different lens types are used. A smoother curve could be drawn for each lens type. The 4X projection lens below the shaded area is limited in aperture and therefore resolution because of the required depth of focus. The 10X step-and-repeat lens is a very reliable point as many designers have designed lenses having these parameters. The step-and-repeat lens is described in detail in another paper in this issue.